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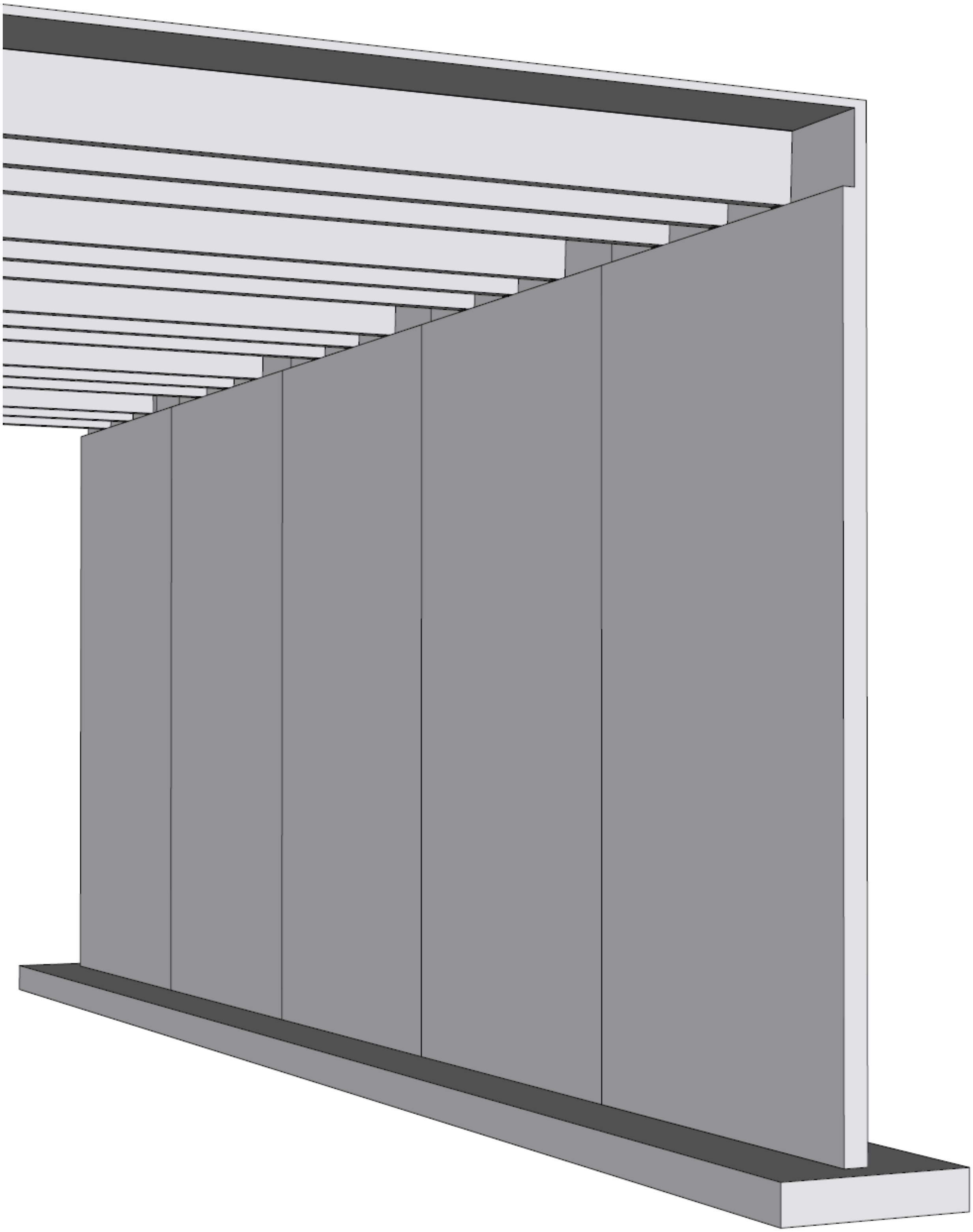
Reinforced Concrete Tilt-Up Wall Panel Analysis and Design (CSA A23.3-14)



Reinforced Concrete Tilt-Up Wall Panel Analysis and Design (CSA A23.3-14)

Tilt-up is form of construction with increasing popularity owing to its flexibility and economics. Tilt-up concrete is essentially a precast concrete that is site cast instead of traditional factory cast concrete members. A structural reinforced concrete tilt-up wall panel in a single-story warehouse (big-box) building provides gravity and lateral load resistance for the following applied loads from three roof joists bearing in wall pockets in addition to the wind:

Roof dead load = 10.5 kN per joist

Roof live load = 11.0 kN per joist

Wind load = 1.5 kN/m^2

The assumed tilt-up wall panel section and reinforcement are investigated after analysis to verify suitability for the applied loads then compared with numerical analysis results obtained from spWall engineering software program from StructurePoint.

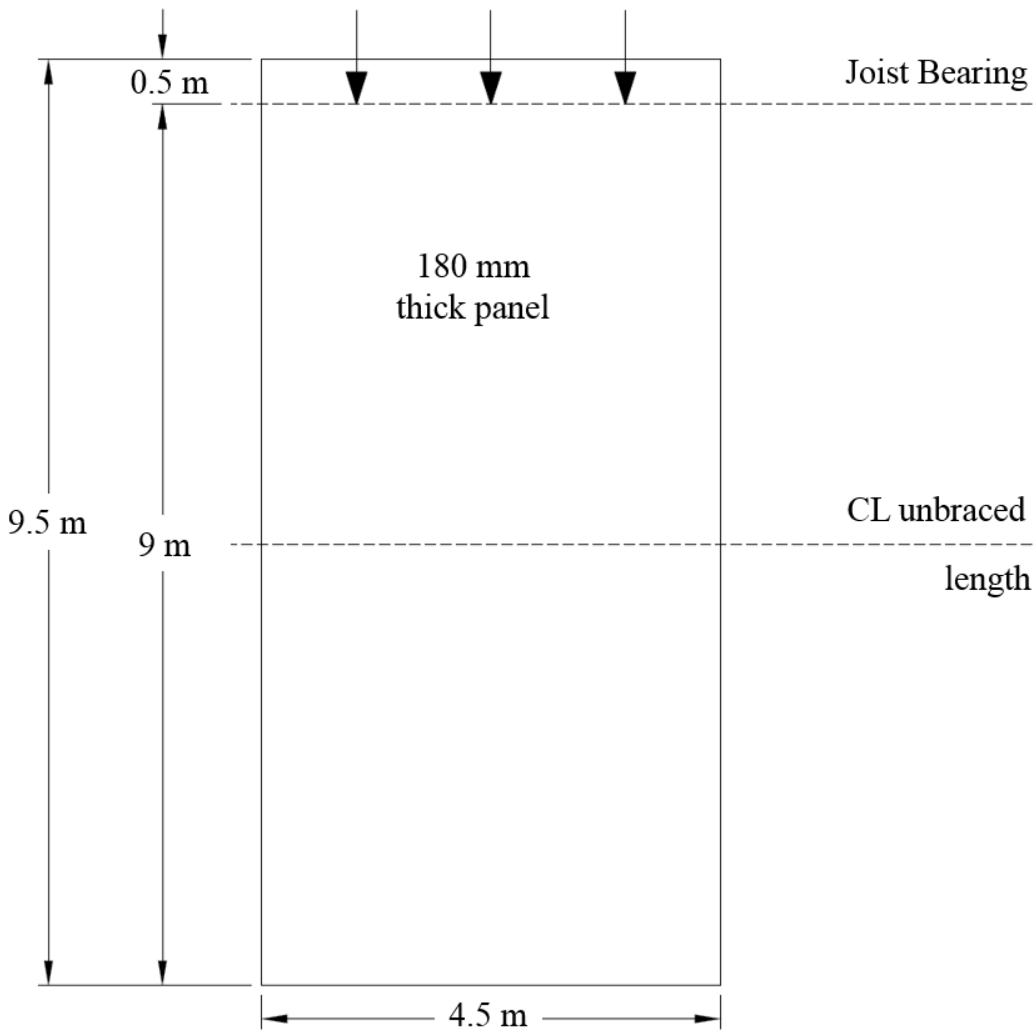


Figure 1 – Reinforced Concrete Tilt-Up Wall Panel Geometry

Contents

Code

Design of Concrete Structures (CSA A23.3-14) and Explanatory Notes on CSA Group standard A23.3-14 "Design of Concrete Structures"

Reference

Design Guide for Tilt-Up Concrete Panels, ACI 551.2R-15, 2015, Example B.1

spWall Engineering Software Program Manual v5.01, STRUCTUREPOINT, 2016

Design Data

f_c' = 25 MPa normal weight concrete (w_c = 24 kN/m^3)

f_y = 400 MPa

Wall length = l_c = 9.5 m – 0.5m = 9.0 m

Assumed wall thickness = 180 mm

Assumed eccentricity = e_{cc} = 75 mm

Assumed vertical reinforcement: 20 – 20M (single layer)

1. Minimum Vertical Reinforcement

$$\rho_l = \frac{A_{v,vertical}}{b \times h} = \frac{6,000}{4,500 \times 180} = 0.0074$$ ***CSA A23.3-14 (3.2)***

$$\rho_{l,\min} = 0.0015$$ ***CSA A23.3-14 (23.2.4)***

$$\rho_l = 0.0074 \geq \rho_{l,\min} = 0.0015 \text{ (o.k)}$$

$$s_{l,\max} = \text{smallest of} \begin{Bmatrix} 3 \times h \\ 500 \text{ mm} \end{Bmatrix} = \text{smallest of} \begin{Bmatrix} 3 \times 180 \\ 500 \text{ mm} \end{Bmatrix} = \text{smallest of} \begin{Bmatrix} 540 \text{ mm} \\ 500 \text{ mm} \end{Bmatrix} = 500 \text{ mm}$$ ***CSA A23.3-14 (14.1.8.4)***

$$s_{l,provided} = \frac{4,500}{20} = 225 \text{ mm} \leq s_{l,\max} = 500 \text{ mm} \;(\textbf{o.k.})$$

2. Tilt-Up Wall Panels Analysis and Design

Tilt-up concrete panels can be analyzed and designed using the Clause of 23 of the CSA A23.3-14. Tilt-up panels are slender vertical flexural slabs that resist lateral wind or seismic loads and are subject to very low axial stresses. Because of their high slenderness ratios, they shall be designed for second-order P-Δ effects to ensure structural stability and satisfactory performance under specified loads. Therefore the method presented in clause 23.3 used to analysis and evaluate the wall. The method is applicable when the conditions summarized below are met:

- The wall can be designed as simply supported ***CSA A23.3-14 (23.3.1.1)***
- The effective panel height shall be center to center distance between supports. ***CSA A23.3-14 (23.2.1)***
- The minimum panel thickness should be 140 mm ***CSA A23.3-14 (23.2.2)***
- The maximum effective height to thickness ratio shall be 50 ***CSA A23.3-14 (23.2.3)***
- Vertical stress should be less than $0.09\phi_c f_c^{'}$ ***CSA A23.3-14 (23.3.1.2)***

3. Tilt-Up Wall Structural Analysis

Using Clause 23.3, calculate factored loads as follows for each of the considered load combinations:

3.1. Applied loads

$$\text{Wall self-weight} = \frac{180}{1,000} \times 4.5 \times \left(\frac{9}{2} + 0.5\right) \times 24 = 97.20 \text{ kN}$$

$$P_{DL} = 3 \times 10.5 = 31.5 \text{ kN}$$

$$P_{LL} = 3 \times 11 = 33 \text{ kN}$$

$$w = 1.5 \text{ kN/m}^2$$

3.2. Maximum wall forces

Calculate maximum factored wall forces in accordance with 23.3.1 including moment magnification due to second order (P-Δ) effects. Load combination U = 1.25 *D* × 1.5 *L* × 0.4 *W* is considered in this example:

$$P_{tf} = 1.25 \times 31.5 + 1.5 \times 33.0 = 88.88 \text{ kN}$$

$$P_{wf} = 1.25 \times 92.7 = 121.5 \text{ kN}$$

$$P_f = P_{wf} + P_{tf} = 88.88 + 121.50 = 210.38 \text{ kN}$$

$$W_f = 0.4 \times 1.5 \times 4.5 \text{ m} = 2.7 \text{ kN/m}$$

$$M_f = M_b \delta_b$$ ***CSA A23.3-14 (Eq. 23.2)***

Where:

$$\delta_b = \frac{1}{1 - \dfrac{P_f}{\phi_m K_{bf}}} = \frac{1}{1 - \dfrac{210.38 \times 10^3}{0.75 \times 6.78 \times 10^5}} = 1.71$$

$$M_b = \frac{W_f \times \ell^2}{8} + P_{tf} \times \frac{e}{2} + \left(P_{wf} + P_{tf}\right) \times \Delta_o$$

$$M_b = \frac{2.7 \times 9.0^2}{8} + 88.88 \times \frac{0.075}{2} + \left(121.50 + 88.88\right) \times 0.0225 = 35.40 \text{ kN.m}$$

$$M_f = M_b \delta_b = 35.40 \times 1.71 = 60.40 \text{ kN.m}$$

Where M_b is the maximum factored moment in panel at load stage which deflection is computed, not including P-Δ effects. ***CSA A23.3-14 (23.3.1.3)***

$$E_c = (3,300\sqrt{f_c^{'}} + 6,900)\left(\frac{\gamma_c}{2,300}\right)^{1.5} = (3,300\sqrt{25} + 6,900)\left(\frac{2,447}{2,300}\right)^{1.5} = 25,684 \text{ MPa}$$ ***CSA A23.3-14(8.6.2.2)***

$$I_{cr} = \frac{bc^3}{3} + \frac{E_s}{E_c} A_{s,eff} \left(d - c\right)^2$$ ***CSA A23.3-14(23.3.1.3)***

Calculate the effective area of longitudinal reinforcement in a slender wall for obtaining an approximate cracked moment of inertia.

$$A_{s,eff} = A_s + \frac{P_f}{\phi_s f_y}\left(\frac{h}{2d}\right) = 6,000 + \frac{310.38}{0.85 \times 400}\left(\frac{180}{2 \times 90}\right) = 6,619 \text{ in.}^2$$ ***CSA A23.3-14(Eq. 23.4)***

The following calculation are performed with the effective area of steel in lieu of the actual area of steel.

$$a=\frac{A_{se}\times f_y}{\alpha_1\times f_c^{'}\times b}=\frac{6,619\times 400}{0.81\times 25\times(4,500)}=28.96\text{ mm}$$

$$c=\frac{a}{\beta_1}=\frac{28.96}{0.91}=31.92\text{ mm}$$

$$\alpha_1=0.85-0.0015f_c^{'}=0.81>0.67$$ **CSA A23.3-14 (10.1.7)**

$$\beta_1=0.97-0.0025f_c^{'}=0.91>0.67$$ **CSA A23.3-14 (10.1.7)**

$$I_{cr}=\frac{bc^3}{3}+\frac{E_s}{E_c}A_{s,eff}(d-c)^2$$ **CSA A23.3-14 (23.3.1.3)**

$$K_{bf}=\frac{48E_cI_{cr}}{5l^2}=\frac{48\times 25,684\times 2.23\times 10^8}{5\times(9,000)^2}=6.78\times 10^5$$

3.3. Limit of c/d for yielding of reinforcement **CSA A23.3-14(10.5.2)**

$$\frac{c}{d}\le\frac{700}{700+f_y}\rightarrow 0.35\le 0.64$$

Therefore, reinforcement can be assumed yielded.

4. Tilt-Up Wall Cracking Moment Capacity (M_{cr})

Determine f_r = Modulus of rapture of concrete and I_g = Moment of inertia of the gross uncracked concrete section to calculate M_{cr}

$$f_r=0.6\lambda\sqrt{f_c^{'}}=0.6\times 1.0\times\sqrt{25}=3.0\text{ MPa}$$ **CSA A23.3-14 (Eq.8.3)**

$$I_g=\frac{l_wh^3}{12}=\frac{4,500\times 180^3}{12}=2.19\times 10^9\text{ mm}^4$$

$$y_t=\frac{h}{2}=\frac{190}{2}=80\text{ mm}$$

$$M_{cr}=\frac{f_rI_g}{y_t}=\frac{(3.0/2)\times(2.19\times 10^9)}{90}\times 10^{-6}=36.45\text{ kN.m}$$ **CSA A23.3-14 (Eq.9.2)**

f_r should be taken as half of the value given in Eq.8.3 **CSA A23.3-14 (9.8.2.3)**

5. Tilt-Up Wall Factored Moment Resistance (M_r)

For load combination #1:

$$M_r=\phi_s\times A_{se}\times f_y\times\left(d-\frac{a}{2}\right)=0.85\times 6,619\times 400\times\left(90-\frac{28.96}{2}\right)/10^6=169.94\text{ kN.m}$$

$$M_r=169.94\text{ kN.m}>M_f=60.40\text{ kN.m }(\textbf{o.k.})$$

6. Tilt-Up Wall Vertical Stress Check

$$\frac{P_f}{A_g} = \frac{210.38\times10^3}{180\times(4,500)\times10^6} = 0.26 \text{ MPa} < 0.09\phi_c f_c' = 0.09\times0.65\times25 = 1.46 \text{ MPa } (\textbf{o.k.})$$ ***CSA A23.3-14 (23.3.12)***

7. Tilt-Up Wall Shear Stress Check

In-plane shear is not evaluated since in-plane shear forces are not applied in this example. Out-of-plane shear due to lateral load should be checked against the shear capacity of the wall. By inspection of the maximum shear forces, it can be determined that the maximum shear force is under 30 kN width. The wall has a shear capacity approximately 190 kN width and no detailed calculations are required by engineering judgement. (See figure 6 for detailed shear force diagram).

8. Tilt-Up Wall Mid-Height Deflection (Δ_s)

The maximum out-of-plane deflection (Δ_s) under specified lateral and vertical loads shall not exceed l/100, but it shall not be greater than can be tolerated by attached structural or non-structural elements. The horizontal mid-height deflection may be computed as follows: ***CSA A23.3-14 (23.3.2)***

$$\Delta_s = \frac{5M_s\ell^2}{48E_cI_e} = \frac{M_s}{K_{bs}}$$ ***CSA A23.3-14 (Eq. 23.5)***

Where

$$M_s = M_{bs}\delta_{bs}$$

Where M_{bs} is the maximum moment in panel due to service loads at load stage at which deflection is computed, not including P-Δ effects.

$$M_{bs} = \frac{W_s\ell^2}{8} + P_{ts}\frac{e}{2} + (P_{ws} + P_{ts})\Delta_o$$

$$I_e = I_{cr} + (I_g - I_{cr})\left[\frac{M_{cr}}{M_s}\right]^3 \le I_g$$

Iterative procedure is used to determine Δ_s (since I_e is a function of M_s) as follows:

Assume M_s = 78.2 kN.m

$$K_{bs} = \frac{48E_cI_e}{5\ell^2} = \frac{48\times25,684\times4.22\times10^8}{5\times9,000^2} = 1.28\times10^6$$

$$P_s = P_{ws} + P_{ts} = 97.20 + 64.50 = 161.70 \text{ kN}$$

$$M_{bs} = \frac{(1.5\times4.5)\times9^2}{8} + 64.5\times\frac{75}{2\times1,000} + (97.2+64.5)\times\frac{22.5}{1,000} = 68.35 \text{ kN.m}$$

$$\delta_{bs} = \frac{1}{1-\dfrac{P_s}{K_{bs}}} = \frac{1}{1-\dfrac{161.7}{1.28\times10^6}} = 1.14 \ge 1.0$$

$M_s = 68.35 \times 1.14 = 78.2 \text{ kN.m}$

The assumption that M_s = 78.2 kN.m is correct.

$$\Delta_s = \frac{M_s}{K_{bs}} = \frac{78.2 \times 10^3}{1.28 \times 10^6} \times \frac{10^3 \text{ mm}}{1 \text{ m}} = 60.94 \text{mm}$$

$$\Delta_s = 60.94 \text{ mm} < \frac{l_c}{100} = \frac{9,000}{100} = 90 \text{ mm} \quad (\textbf{o.k.})$$

The wall is adequate with 20 – 20M vertical reinforcement and 180 mm thickness.

9. Tilt-Up Wall Panel Analysis and Design – spWall Software

spWall is a program for the analysis and design of reinforced concrete shear walls, tilt-up walls, precast walls and Insulate Concrete Form (ICF) walls. It uses a graphical interface that enables the user to easily generate complex wall models. Graphical user interface is provided for:

- Wall geometry (including any number of openings and stiffeners)
- Material properties including cracking coefficients
- Wall loads (point, line, and area),
- Support conditions (including translational and rotational spring supports)

spWall uses the Finite Element Method for the structural modeling, analysis, and design of slender and non-slender reinforced concrete walls subject to static loading conditions. The wall is idealized as a mesh of rectangular plate elements and straight line stiffener elements. Walls of irregular geometry are idealized to conform to geometry with rectangular boundaries. Plate and stiffener properties can vary from one element to another but are assumed by the program to be uniform within each element.

Six degrees of freedom exist at each node: three translations and three rotations relating to the three Cartesian axes. An external load can exist in the direction of each of the degrees of freedom. Sufficient number of nodal degrees of freedom should be restrained in order to achieve stability of the model. The program assembles the global stiffness matrix and load vectors for the finite element model. Then, it solves the equilibrium equations to obtain deflections and rotations at each node. Finally, the program calculates the internal forces and internal moments in each element. At the user's option, the program can perform second order analysis. In this case, the program takes into account the effect of in-plane forces on the out-of-plane deflection with any number of openings and stiffeners.

In spWall, the required flexural reinforcement is computed based on the selected design standard (CSA A23.3-14 is used in this example), and the user can specify one or two layers of wall reinforcement. In stiffeners and boundary elements, spWall calculates the required shear and torsion steel reinforcement. Wall concrete strength (in-plane and out-of-plane) is calculated for the applied loads and compared with the code permissible shear capacity.

For illustration and comparison purposes, the following figures provide a sample of the input modules and results obtained from a spWall model created for the reinforced concrete wall in this example.

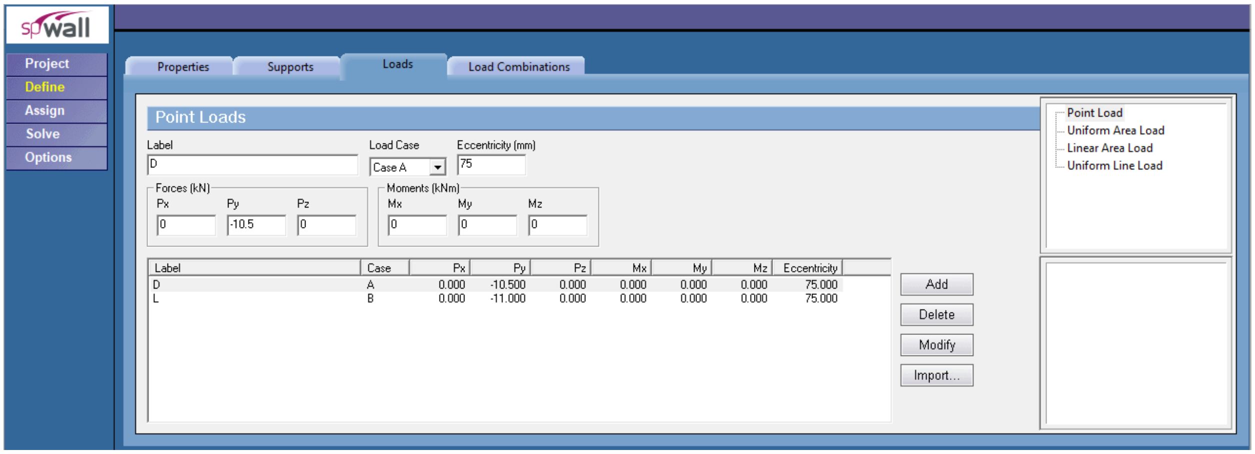


Figure 2 –Defining Loads for Tilt-Up Wall Panel (spWall)

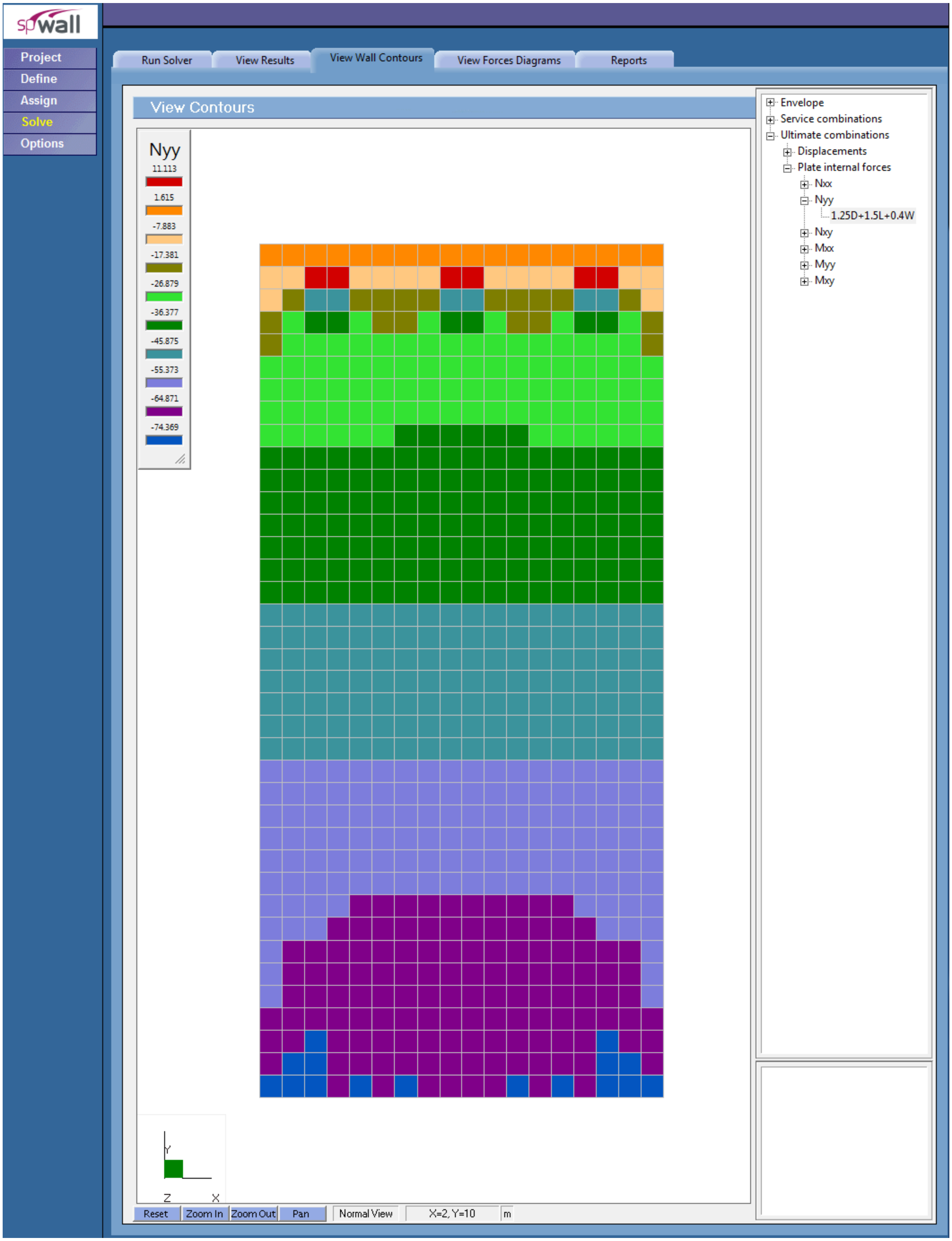


Figure 3 –Factored Axial Forces Contour Normal to Tilt-Up Wall Panel Cross-Section (spWall)

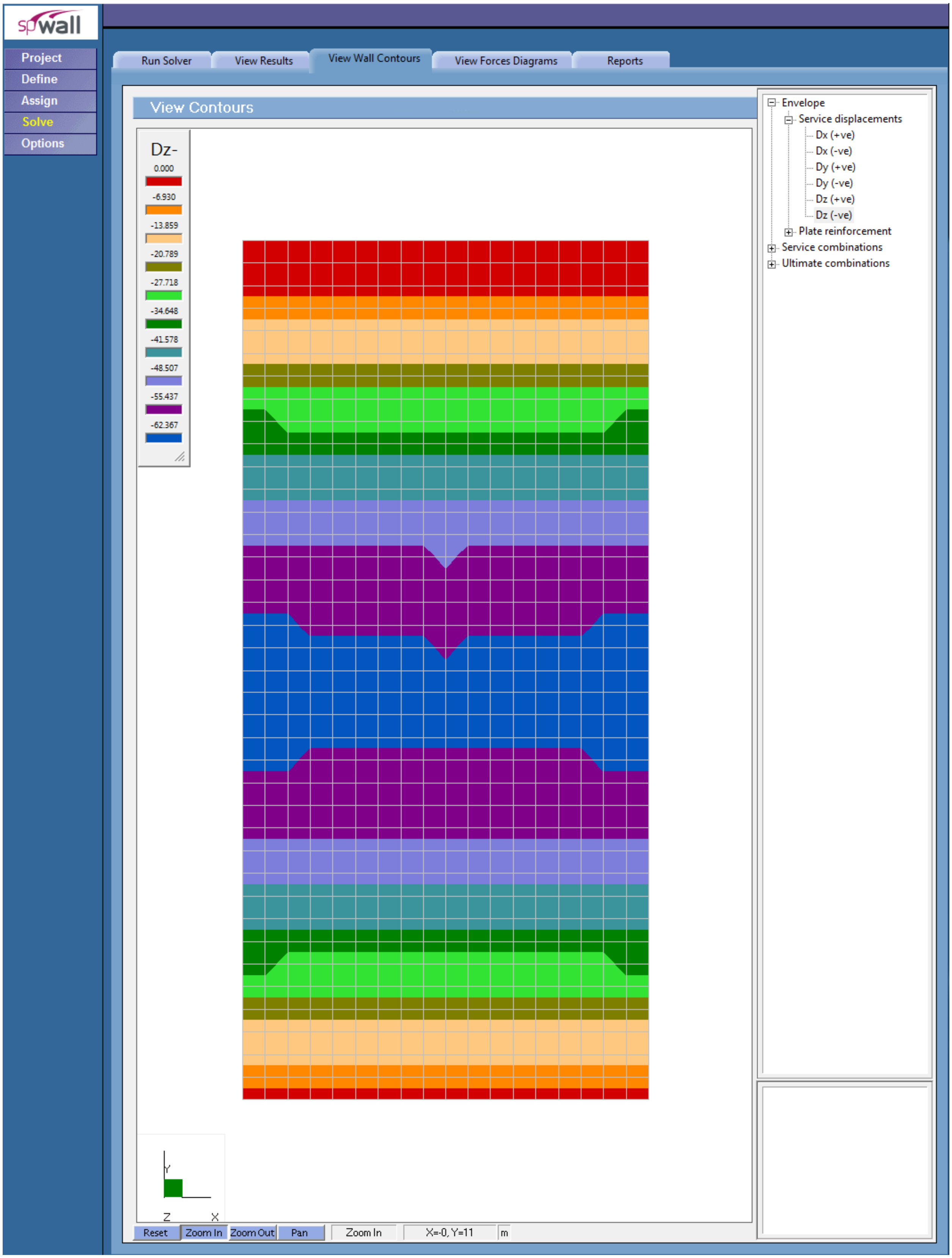


Figure 4 – Tilt-Up Wall Panel Lateral Displacement Contour (Out-of-Plane) (spWall)

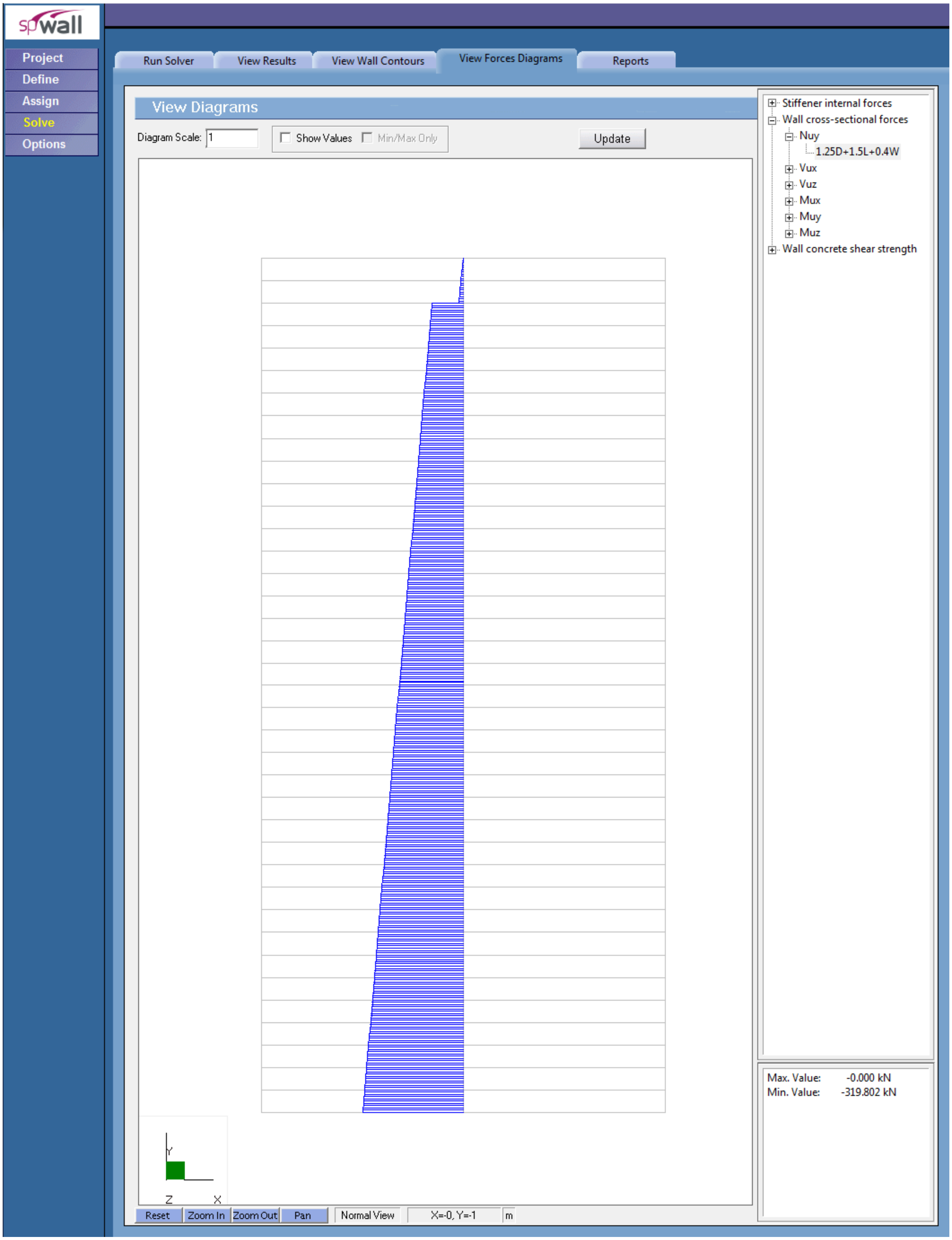


Figure 5 – Tilt-Up Wall Panel Axial Load Diagram (spWall)

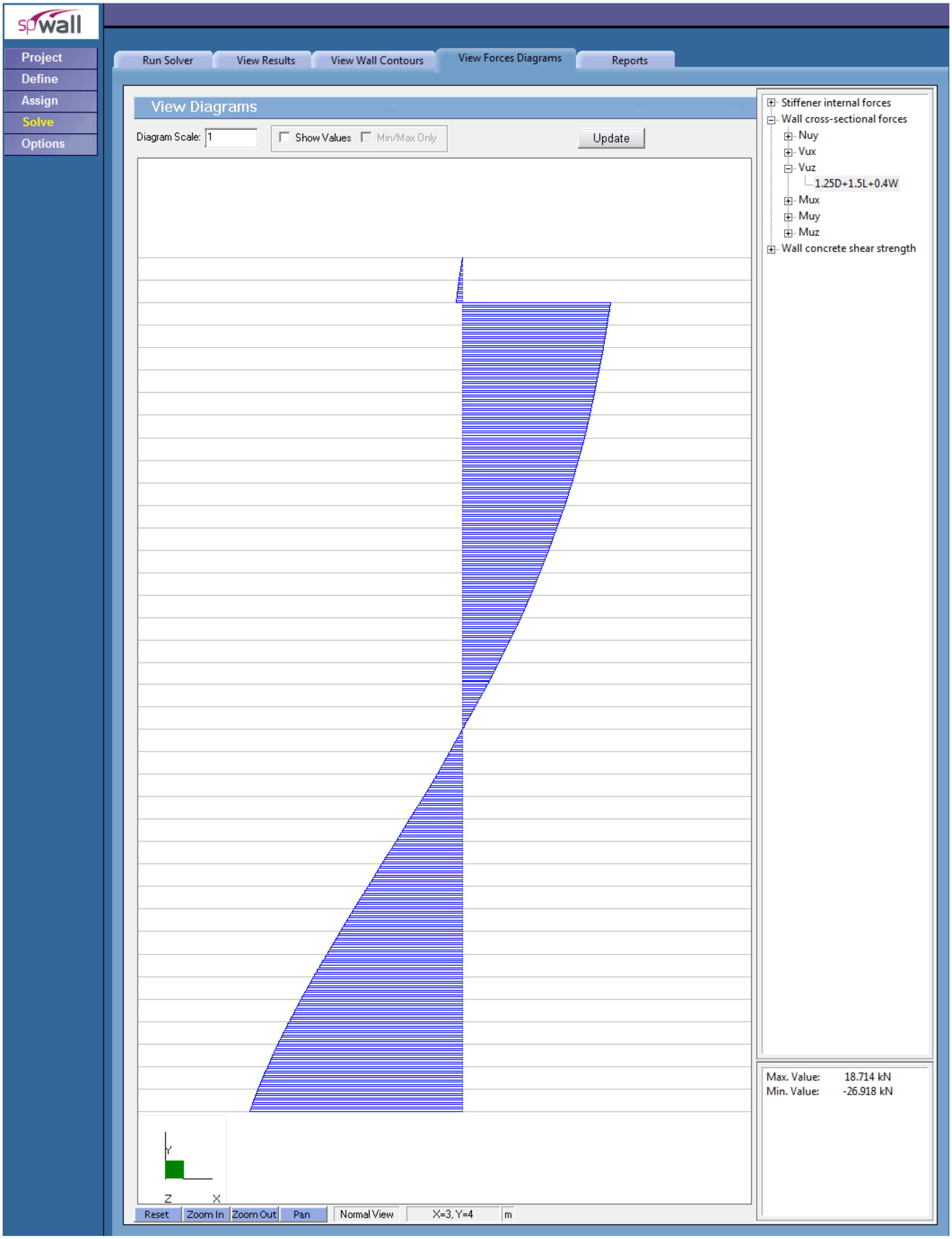


Figure 6 – Out-of-plane Shear Diagram (spWall)

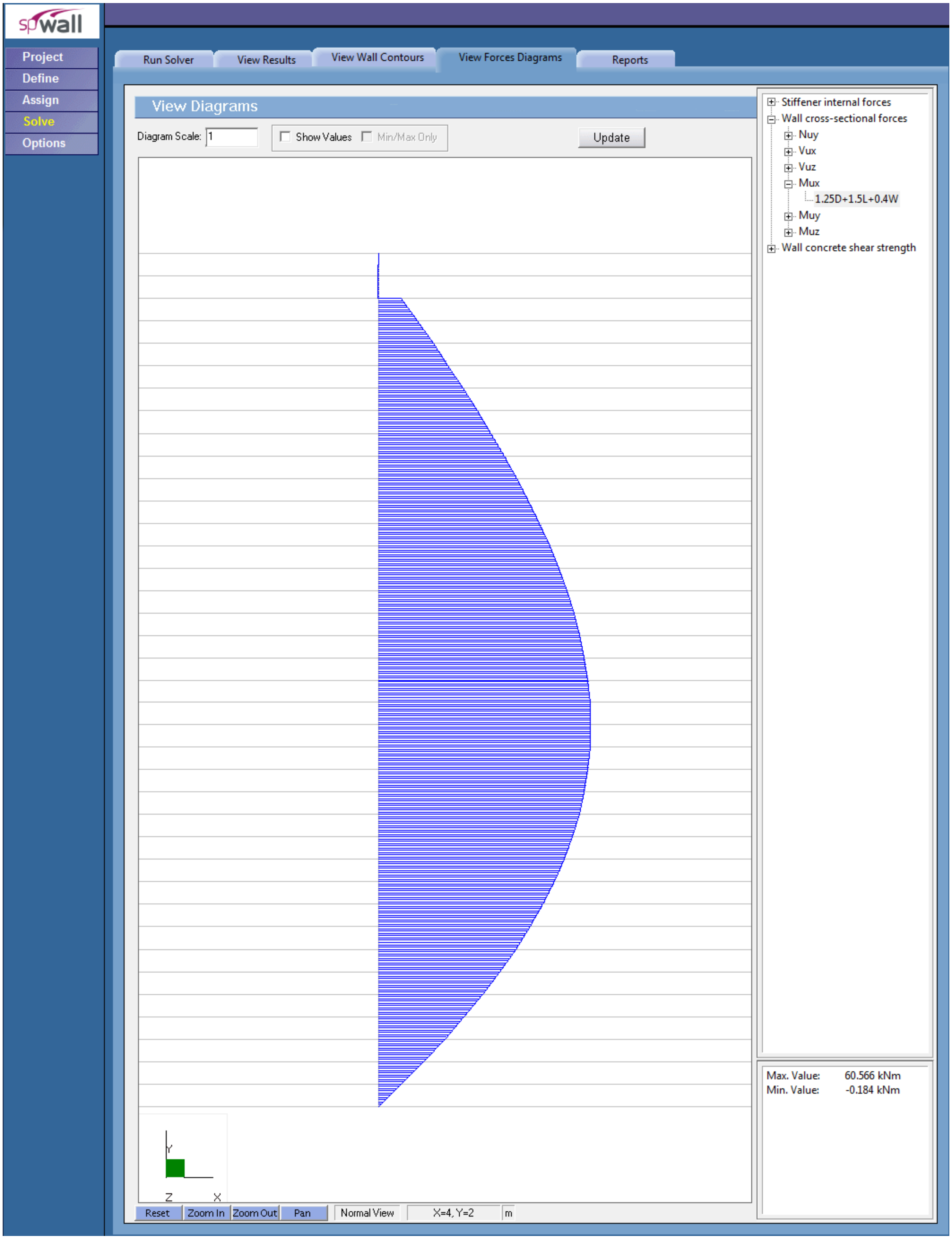


Figure 7 – Tilt-Up Wall Moment Diagram (spWall)

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ULTIMATE COMBINATIONS: CROSS-SECTIONAL FORCES
=============================================
     Force (Vux, Nuy, Vuz): kN, Moment (Mux, Muy, Muz): kNm
     Y-coordinate, X-centroid: m

   Ultimate combination: 1.25D+1.5L+0.4W

     ___Horizontal Wall Section____ ___________In-plane Forces__________ _________Out-of-plane Forces____
     No.  Y-coordinate  X-centroid       Vux          Nuy          Muz          Vuz          Mux          Muy
     ---- ------------ ------------ ------------ ------------ ------------ ------------ ------------ -------
      19-         4.500        2.250 -5.1159e-013 -2.1042e+002  1.4943e-011  1.6363e+000  6.0353e+001  1.0920
      19+         4.500        2.250 -3.4931e-014 -2.1042e+002 -1.2946e-012  1.6363e+000  6.0350e+001 -4.3015
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Figure 8 – Tilt-Up Wall Panel Cross-Sectional Forces (spWall)

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SERVICE COMBINATIONS: NODAL DISPLACEMENTS
=========================================
   Displacement (Dx, Dy, Dz): mm

   Service combination: Service

    Node      Dx          Dy          Dz
   ----- ---------- ---------- ----------
     343 -3.57e-003 -4.64e-002 -6.24e+001
     344 -3.18e-003 -4.65e-002 -6.18e+001
     345 -2.80e-003 -4.66e-002 -6.13e+001
     346 -2.40e-003 -4.67e-002 -6.09e+001
     347 -2.01e-003 -4.67e-002 -6.05e+001
     348 -1.61e-003 -4.68e-002 -6.03e+001
     349 -1.21e-003 -4.68e-002 -6.01e+001
     350 -8.11e-004 -4.68e-002 -5.99e+001
     351 -4.06e-004 -4.68e-002 -5.98e+001
     352 -4.30e-015 -4.68e-002 -5.98e+001
     353  4.06e-004 -4.68e-002 -5.98e+001
     354  8.11e-004 -4.68e-002 -5.99e+001
     355  1.21e-003 -4.68e-002 -6.01e+001
     356  1.61e-003 -4.68e-002 -6.03e+001
     357  2.01e-003 -4.67e-002 -6.05e+001
     358  2.40e-003 -4.67e-002 -6.09e+001
     359  2.80e-003 -4.66e-002 -6.13e+001
     360  3.18e-003 -4.65e-002 -6.18e+001
     361  3.57e-003 -4.64e-002 -6.24e+001
```

$D_{z,avg}$ = 60.83 mm

Figure 9 – Tilt-Up Wall Panel Displacement at Critical Section (Service Combinations) (spWall)

10. Design Results Comparison and Conclusions

Table 1 – Comparison of Tilt-Up Wall Panel Analysis and Design Results			
Solution	M_f (kN.m)	N_f (kN)	$D_{z,service}$ (mm)
Hand	60.4	210.4	60.94
spWall	60.3	210.4	60.83

The results of all the hand calculations used illustrated above are in agreement with the automated exact results obtained from the spWall program.

In column and wall analysis, section properties shall be determined by taking into account the influence of axial loads, the presence of cracked regions along the length of the member, and the effect of load duration (creep effects). CSA A23.3 permits the use of moment of inertia values of 0.70 I_g for uncracked walls and $0.35I_g$ for cracked walls.

CSA A23.3-14 (10.14.1.2)

In spWall program, these effects are accounted for where the user can input reduced moment of inertia using "cracking coefficient" values for plate and stiffener elements to effectively reduce stiffness. Cracking coefficients for out-of-plane (bending and torsion) and in-plane (axial and shear) stiffness can be entered for plate elements. Because the values of the cracking coefficients can have a large effect on the analysis and design results, the user must take care in selecting values that best represent the state of cracking at the particular loading stage. Cracking coefficients are greater than 0 and less than 1.

At ultimate loads, a wall is normally in a highly cracked state. The user could enter a value of out-of-plane cracking coefficient for plates of $I_{cracked}/I_{gross}$ based on estimated values of A_s. After the analysis and design, if the computed value of A_s greatly differs from the estimated value of A_s, the analysis should be performed again with new values for the cracking coefficients. A member resistance factor of 0.75 can be used to reduce the calculated bending stiffness of the concrete section in accordance with CSA A23.3-14 Clause 23.3.1.3.

At service loads, a wall may or may not be in a highly cracked state. For service load deflection analysis, a wall panel should be modeled with an out-of-plane cracking coefficient of ($I_{effective}/I_{gross}$).

Check "Reinforced Concrete Tilt-Up Wall with Opening Panel Analysis and Design (ACI 551)" example for more details about cracking coefficient optimization for tilt-up walls.